EECS170A Fall 2004 **2nd Midterm Exam** Name:__________________________

11-09-2004 ID no.:__________________________

Sec.B: Peter Burke 3:30 to 4:50 pm

1A	1B	2	3A	3B	3C	3D	3E	Total
/15	/15	/20	/10	/10	/10	/10	/10	/100

THREE PROBLEMS TOTAL.

DO NOT BEGIN THE EXAM UNTIL YOU ARE TOLD TO DO SO.

PROBLEM ONE: (30 points)

1) For a piece of Si at 300 K, $N_D = 10^{17}$ cm^{-3}:
   a. Find the mobility μ_n of electrons to within 10% (15 points)

Method 1:
μ_n = 801 cm^2/V-s (from Figure 3.5a)
Accepted answers: 721 – 881 cm^2/V-s

No partial credit. 15 points if answer is within range.

Method 2:

ρ = .078 Ω-cm (from Figure 3.8a)	***5 pts for correct value from graph***
$\mu_n = 1/nq\rho$	***5 pts for correct equation***
= 1/(10^{17} cm^{-3})(1.6x10^{-19}C)(.078 Ω-cm)	
= 801 cm^2/V-s	***5 pts for right answer within 10%***

   b. Find the diffusion constant D_N of electrons to within 10% (15 points)

$D_N = \mu_n kT/q$	***5 pts for right equation***
= (801 cm^2/V-s)(.0259V)	***5 pts for putting in numbers correctly***
= 20.7 cm^2/s	***5 pts for answer in correct range***

Accepted answers: 18.6 – 22.8 cm^2/s

PROBLEM TWO: (20 points)

Some baseline temperatures in the three temperature scales:

temperature	kelvins	degrees Celsius	degrees Fahrenheit
symbol	**K**	**°C**	**°F**
boiling point of water	373.15	100.	212.
melting point of ice	273.15	0.	32.
absolute zero	0.	-273.15	-459.67

2) A p-n diode is reverse biased at – 1 V and cooled to the temperature of the melting point of ice (T = 273 K). At that temperature, the current is 1 pA.

The diode is now put into a pot of boiling water, so that its temperature is 373 K.
What is the current now, assuming the voltage is still – 1 V?

This problem cannot be solved exactly, since N_A and N_D are not given.
Therefore, and exact solution will not be required to get full credit on this problem.

Generally speaking, there are 2 ways to do this problem:
Use lecture notes, or use book.

<u>METHOD I: USE LECTURE NOTES</u>

In class we showed the

$$I(V_A) = (\text{constant}) e^{-\frac{qV_{bi}}{k_B T}} \left(e^{-\frac{qV_A}{k_B T}} - 1 \right)$$

At V_A=-1 V,

$$\left(e^{-\frac{qV_A}{k_B T}} - 1 \right) \approx 1$$

for T=273 K and T = 373 K.

Therefore, $I(V_A = -1V) \approx -(\text{constant}) e^{-\frac{qV_{bi}}{k_B T}}$

Assuming the constant is independent of temperature (not exactly true but we didn't cover in lecture), we have:

$$\frac{I(V_A=-1V)\big|_{273K}}{I(V_A=-1V)\big|_{373K}} = \frac{-(\text{constant})e^{-\frac{qV_{bi}}{k_B 273K}}}{-(\text{constant})e^{-\frac{qV_{bi}}{k_B 373K}}} = \frac{e^{-\frac{qV_{bi}}{k_B 273K}}}{e^{-\frac{qV_{bi}}{k_B 373K}}} = e^{e^{-\frac{qV_{bi}}{k_B 273K}+\frac{qV_{bi}}{k_B 373K}}}$$

Now, V_{bi} is not given so quantitatively this is as far as you can go.
But a typical value of V_{bi} is 0.5 V. So for a typical value:

$$\frac{I(V_A=-1V)\big|_{273K}}{I(V_A=-1V)\big|_{373K}} = e^{e^{-\frac{q(0.5V)}{k_B 273K}+\frac{q(0.5V)}{k_B 373K}}} = e^{-21.23+15} = e^{-5.75} = 0.003$$

So

$$I(V_A=-1V)\big|_{373K} = \frac{I(V_A=-1V)\big|_{273K}}{0.003} = 333pA$$

<u>METHOD II: USE BOOK</u>

Book eq. 6.29

$$I(V_A) = I_0\left(e^{-\frac{qV_A}{k_B T}} - 1\right)$$

At V_A=-1 V,

$$\left(e^{-\frac{qV_A}{k_B T}} - 1\right) \approx 1$$

for T=273 K and T = 373 K.
Therefore, $I(V_A=-1V) \approx I_0$
Book eq. 6.30

$$* \; I_0 = qAn_i^2\left(\frac{D_N}{L_N}\frac{1}{N_A} + \frac{D_p}{L_p}\frac{1}{N_D}\right)$$

q,A, N_A, N_D independent of temperature.
Book figure 2.20:
n_i (T=273 K) = 10^9 cm^{-3}
n_i (T=373 K)= 10^{12} cm^{-3}

$$\frac{D_N}{L_N} = \frac{D_N}{\sqrt{D_N \tau_n}} = \frac{\sqrt{D_N}}{\sqrt{\tau_n}}$$

Approximately, τ_n independent of temperature.
By Einstein (book eqn. 3.25)

$$\sqrt{D_N} = \sqrt{\frac{k_B T \mu_n}{q}}$$

μ_n depends on temperature, as per book figure 3.7: μ_n decreases with temperature in a way that depends on N_A, N_D.

The most it decreases by is about a factor of 2. So $\sqrt{D_N}$ changes some with temperature, but not by more than a factor of 10.
Similar arguments hold for $\sqrt{D_P}$
So the factor in parenthesis in equation * above changes by a small amount.
However, the n_i^2 factor changes by a large amount, and this dominates.
So if we neglected the factor in parentheses we have:

$$\frac{I(V_A=-1V)\big|_{273K}}{I(V_A=-1V)\big|_{373K}} = \frac{I_0\big|_{273K}}{I_0\big|_{373K}} = \frac{n_i^2\big|_{273K}}{n_i^2\big|_{373K}} = \frac{10^{18}}{10^{24}} = 10^{-6}$$

So

$$I(V_A=-1V)\big|_{373K} = \frac{I(V_A=-1V)\big|_{273K}}{0.001} = 10^6\, pA = 1\mu A$$

Using either method, the conclusion is that the current at 373 K is much larger than the current at 273 K for reverse bias, by a large factor.

Grading criteria:

State the ideal diode equation: 10 points
State that at V_A=-1 V,

$$\left(e^{-\frac{qV_A}{k_B T}}-1\right)\approx 1$$

for both T=273 K and T = 373 K, 5 more points.

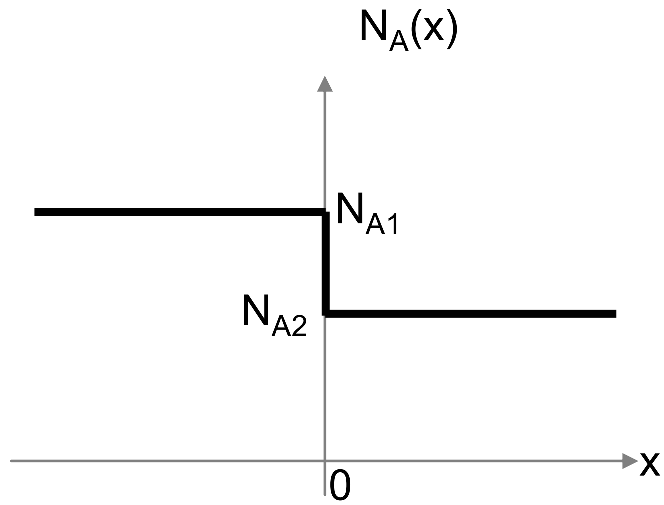
If you assume I_0 independent of temperature, and that all the temperature dependence in I(V) is in the term in parentheses in the ideal diode equation, you are wrong.

If you try to calculate I_o in terms of temperature, 2 more points.

If you come to conclusion that reverse bias current (magnitude) is larger at 373 K than 273 K for the right reasons, 2 more points.

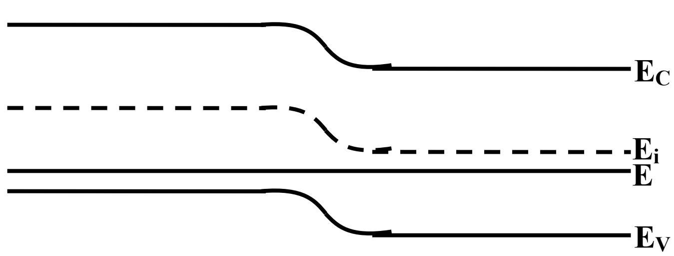
If you actually state quantitatively that the ratio is between 10 and 10^7 (for right reason, not just guess), 1 more point.

PROBLEM THREE: (50 points)



In class we considered a p-n junction. Now, I want you to consider a p-p junction, as shown in the graph above.

3) For a piece of Si with doping profile shown in the graph above,
   a. Draw the equilibrium energy band diagram for the junction, taking the doping to be nondegenerate and $N_{A1} > N_{A2}$. (10 points)



3 pts if E_F remains under E_i to show that they are both p-type
4 pts if $(E_F - E_V)_{left} < (E_F - E_V)_{right}$
3 pts if band bending is smooth, not abrupt

PROBLEM THREE: (50 points)

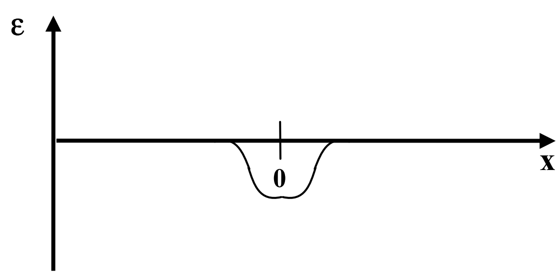
b. Derive an expression for the built-in voltage (V_{bi}) that exists across the junction under equilibrium conditions. (10 points)

$V_{bi} = [(E_{i1} - E_F) - (E_{i2} - E_F)]/q$	**4 pts for initial equation**
$= [kT \ln(N_{A1}/n_i) - kT \ln(N_{A2}/n_i)]/q$	**3 pts for substitution**
$= (kT/q)[\ln(N_{A1}/n_i) - \ln(N_{A2}/n_i)]$	
$= (kT/q) \ln(N_{A1}/N_{A2})$	**3 pts for final equation**

Special case:

5 pts if initial equation has an addition instead of a subtraction and the final answer is $(kT/q) \ln(N_{A1}N_{A2}/n_i^2)$.
2 pts for writing the equation $V_{bi} = [(E_{i1} - E_F) + (E_{i2} - E_F)]/q$
1 pt if you just write $(kT/q) \ln(N_{A1}N_{A2}/n_i^2)$ without showing work.

c. Sketch the electric field as a function of position under equilibrium conditions. (10 points)



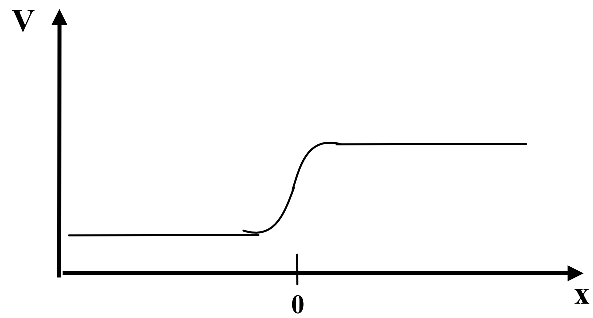
3 pts if correct shape
2 pts if smooth
3 pts if negative
2 pts if centered at 0

Special case:

If you state electric field is slope of the bands but get the graph wrong, 1 point.

PROBLEM THREE: (continued)

d. Sketch the electrostatic potential (voltage) V(x) as a function of position under equilibrium conditions. (10 points)

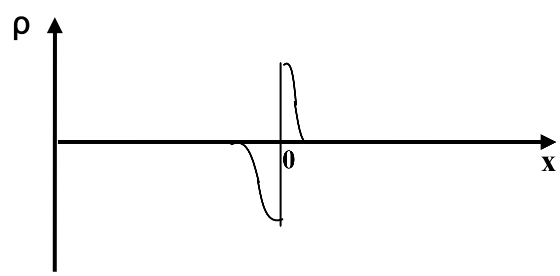


5 pts for correct shape
5 pts for centered at 0

Special case:

5 pts if graph has a sharp transition and is centered at 0.
3 pts if graph has a sharp transition and not centered at 0.

e. Sketch the total charge density ρ(x) as a function of position under equilibrium conditions. (10 points)



4 pts if $x<0$ is negative
4 pts if $x>0$ is positive
2 pts for the shape

Special case:

If you state Poission equation but get the graph wrong, 1 point.